The monitoring system of the Electromagnetic Calorimeter of CMS

P. Verrecchia[a]

[a]CEA-CE Saclay-DSM/DAPNIA/SPP, 91191 Gif-sur-Yvette, France

The physics process that imposes the strictest performance on an Electromagnetic Calorimeter is the intermediate mass Higgs decaying into two photons. The excellent energy resolution requirement conducted CMS to choose a totally active ECAL using lead tungstate crystals. This requirement implies building a monitoring system allowing to maintain a good energy resolution over the full life of the Calorimeter. The low luminosity expected at the begining of LHC operation and the large granularity of the Calorimeter are the main reasons for using the light monitoring system not only to compensate the Calorimeter ageing but also for calibration.

1. INTRODUCTION

In a first step, the design of the light monitoring system and its essential characteristics will be presented as well as a detailed description of the control of the monitoring system (control of the light source by photodetectors located along the distribution chain and the control of the photodetector themselves). A short discussion on the possible choice of the light source will follow, and despite of this uncertainty a typical *suivi* of an irradiation of a crystal performed with a green laser will be shown.
In a second step, the use of the light monitoring system for the calibration of each channel of the Calorimeter will be explained. This part is somewhat formal: the response of the crystal to the injected light and the signal due to electromagnetic showers will be parametrized and the relation between them, which is *a crucial point for the calibration*, will be deduced.
Once computed the calibration coefficients for each individual crystal we finally discuss how their fine tuning will be done using real events (single electrons,$Z^0 \to e^+e^-$ ....).

2. THE LIGHT MONITORING SYSTEM

2.1. Overview

The light monitoring system injects light on each individual crystal through a fiber distribution system which is organised into three distribution levels and follows the geometrical structure of the Electromagnetic Calorimeter which is described in the CMS technical proposal [1].
Outside the detector a light source sends a light impulse on an optical switch which selects a second level module at each monitoring cycle. Each second level modules dispatches the light signal to $\simeq$ 20 first level modules which then dispatch the light signal to individual crystals.
400μm diameter quartz fibers will be used for the transportation of the light from the source to the second level modules and 200μm (or less) from the second level to individual crystals due to the lack of free space in the Electromagnetic Calorimeter area.
At each level of the distribution (optical switch included) the light is monitored by photodetectors such as PIN diodes and photomultipliers (if outside the detector).
The material used for the distribution of the light and its control will remain the same whatever the light source. The main constraint is the following: all the components inside the detector must be radiation resistant.

2.2. Second level modules

Each second level module corresponds to what is called in mechanics a supermodule.
A half longitudinal (in eta) view of the CMS Calorimeters is sketched in the Figure 1. For the barrel, a supermodule constists of four baskets containing $\simeq$ 600 crystals each. There are one supermodule per half barrel and 18 supermodules in phi. For the time being the geometry of the End-Caps is not yet frozen, nevertheless the

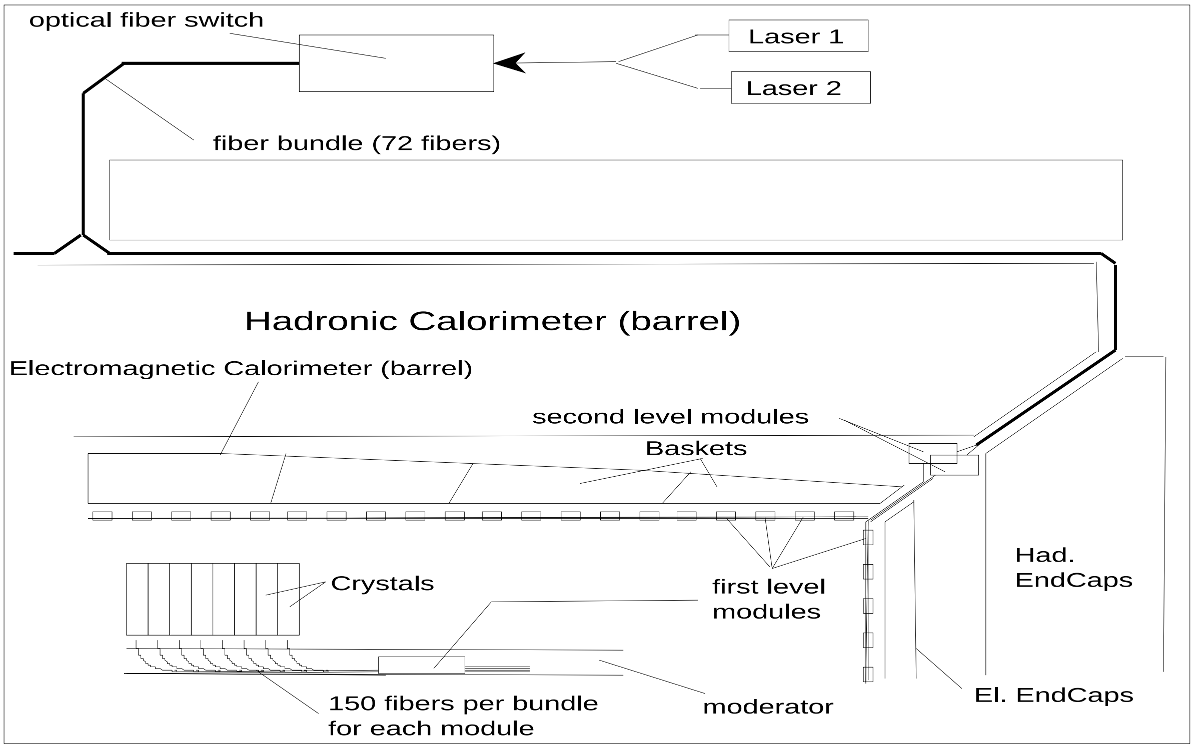

Figure 1. The light monitoring system: overview of the distribution system and details on the injection of the light to individual crystals.

same philosophy will be applied.

A supermodule thus constists of approximatily 2500 crystals. At each monitoring cycle an entire supermodule is illuminated by the light source at a given wavelength.

At this level, the light is monitored by PIN photodiodes.

This control will be discussed in more detail in the description of the first level modules. Nevertheless, the reader may find an analytic approach of the control of the monitoring in a Saclay report [4] and a more general view including the control of the readout electronics in a technical note [2].

2.3. First level modules

The light distribution at this level will be onto 144 crystals in order to follow the trigger clustering. The light will be injected at the front of the crystals. By this front side enter also the particles coming from the vertex.

Due to the size of the connection of the fiber to the crystal (an air gap between the crystal and the extremity of the fiber must be maintained) and the maximum curvature that can be imposed to the fibers, it is intented to install all these fibers into paraffin used as moderator which is located in front of the barrel as shown in the detail of the Figure 1.

At this level, the control of the monitoring system has a big importance because these modules are located at the end of the distribution chain in a region under irradiation.

A simplified logic is shown in Figure 2. Two fibers per distributors are connected to PIN photodiodes (two for safety) for the control of the

light delivered by the source and distributed to the crystals through fibers. Here we must be sure that PIN diodes are not affected by ageing (this problem is not crucial for the second level module). Furthermore one fiber is connected to an APD in order to follow its time evolution independently of the crystal.
An important point is that the fibers going to the crystals, PIN diodes and APD have the same length, otherwise a correction for the time evolution of the fiber transmission a^i is needed.

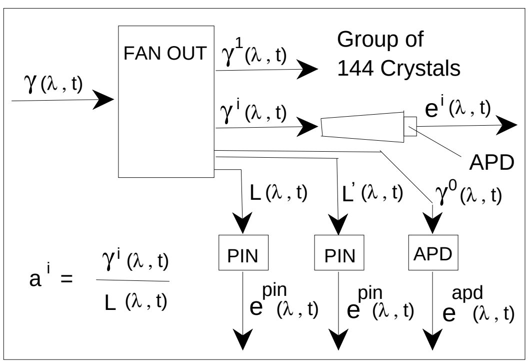

Figure 2. The first level module: distribution of the light onto the crystals and devices for the control of the monitoring system. λ is the wavelength of the injected light and t is the time. The amount of light $L(\lambda, t)$ at the output of the fanout is measured by a PIN as the ratio of the signal $e^{pin}(\lambda, t)$ by its quantum efficiency.

2.4. The light source

The light injection system operates at (at least) two wavelengths, one in the scintillation peak of the lead tungstate and another in the red. This choice allows a better understanding of the radiation damage.
The power of the light source is determined by two considerations:

- crystals are calibrated mainly with a $50 GeV$ electron beam. It is then useful to inject light at the same equivalent energy.
- Following the scheme of the light distribution, 2500 crystals are illuminated at the same time.

From our experience on the monitoring of a few test-beams, these items should be fulfilled by using a source with a power of 100μJ. In this situation the source must send this energy into a small aperture (typically 400μm) for each wavelength.
As a consequence, the possible choices are then a Laser or a Xenon lamp. The choice of the light source is rather a choice between two philosophies: a short versus a long time monitoring. The laser is prefered because it can deliver a pulse 15nsec wide compatible with the scintillation time of the lead tungstate. The Xenon lamp has a long pulse of the order of few 100nsec which will be truncated by the 40nsec shaping time of the readout electronics. Of course, it must be possible nevertheless to perform a monitoring with the Xenon lamp but the interpretation of the results will be much more dificult.

3. CALIBRATION WITH THE LIGHT MONITORING SYSTEM

3.1. The scenario

The calibration of the ECAL Calorimeter will proceed in two steps: a light injection system which compensates as much as possible the rapid evolution of the Calorimeter with time followed by a fine tuning using real events. Here we have two time scales, typically one week to perform a calibration with real events and few hours for the compensation of the calorimeter ageing. These different time scales do not matter, the main point is to have a compensation of the damage produced to the attenuation length of each crystals by radiation precise enough. As an example it can be see in Figure 3 a typical *suivi* performed by a green laser. The response of the crystal to injected light follow the modification of its attenuation length. The rapid evolution of the crystal appears during the first half day of its life, later the evolution is smoother and then easily controlable.
In the meantime statistics on physical events are accumulated. The better the stability on the determination of the absolute energy by the light

monitoring system, the lower the statistics of real events needed for the calibration of each channel of the Calorimeter.
A stability of the order of a few per cent is enough to achieve a quick convergence of the calibration procedure on real events even with a low statistics.

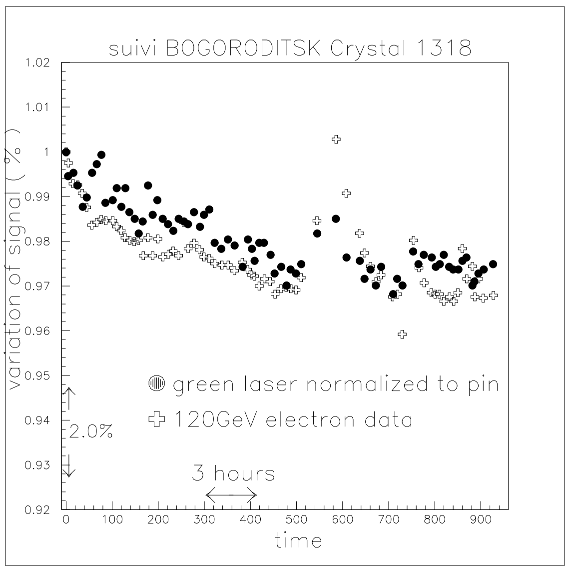

Figure 3. A typical suivi: a Bogoroditsk crystal was irradiated by an high flux 120GeV electrons beam. Compared to the evolution of the response to electrons, the green laser $\lambda = 523\mu m$ data follows the modification of the attenuation length of the crystal. A period of few hours without beam allows a recovery which is also detected by the injected light. Typical errors are 0.5% for both electron data and laser points.

The key of the calibration of the Electromagnetic Calorimeter by the light monitoring system is the relation between the injected light and the electromagnetic shower responses of the crystals. Let me explain how we parametrize the light injected response and the signal due to electromagnetic showers.
I use the following conventions: t is the time, λ is the wavelength of the light injected or produced, T is the temperature and V the voltage bias applied to the APD.

3.2. Light injected response

Here, only the transparence of the crystal is checked as the function of the time, no crystal scintillation with the light monitoring system is produced.
When a crystal is illuminated by the monitoring system the response R of the channel can be written as:

$$R = a\ L(t,\lambda)\ \mathcal{B}(t,\lambda)\ \bar{M}(V,t,T,\lambda) \quad (1)$$

where:

- a is a parameter describing the relative light transmission of the fibers (see Figure 2); it depends on the channel studied (to be correct we should write a_i) because in the same level 1 bundle some differences may exist in the gluing of the fibers on the quartz bar of the distributors or in the polishing and optical contacts.
- L is the number of photons arriving on the PIN diode.
- $\mathcal{B}$ is the transmission of the crystal when it is illuminated by the monitoring system.
- $\bar{M}$ is the product of the quantum efficiency ϵ_Q of the APD and its gain M.

$$\bar{M}(t,\lambda,V,T) = \epsilon_Q(t,\lambda)\ M(V,t,T,\lambda)$$

The measurement of the relative values of a^i is an important point to do before connecting the fiber to the crystal otherwise it will be impossible in practice to distinguish a from $\mathcal{B}$.
Then the light monitoring system gives a good estimation of the product:

$$\mathcal{B}(t,\lambda)\bar{M}(V,t,T,\lambda) \quad (2)$$

for at least two wavelengths. Notice that there is a correspondence between the transmission $\mathcal{B}$ and the attenuation length Λ of the crystals.

If we suppose that there is no reflection or diffusion and the light is injected perpendicularly at the front of the crystal, the following direct correspondence can be written:

$$\mathcal{B}(t,\lambda) \;=\; exp \; - \int \frac{dz}{\Lambda(t,z,\lambda)} \qquad (3)$$

If the time evolution of the APD is well controlled, we then have the control of the mean value of $\Lambda(t,z,\lambda)$ over z (z is the axis along the depth of the crystals).
One important thing is that systematic measurements on the attenuation length (longitudinal and traversal) of all crystals must be performed automatically by the ACCOS machine. Thus we have the possibility after mounting the supermodule to cross-check the monitoring system: the transmission function $\mathcal{B}$ computed from the response R of the channel to light injection, must be compatible with the mean value of the attenuation length over z (previously measured).

3.3. Signal due to particles

The expression of the signal S is:

$$S \;=\; E_0 \int E(z)\, \mathcal{C}(t,z,\lambda) \;\; P(t,T,z,\lambda) \; \bar{M}(V,t,T,\lambda)\; d\lambda \; dz \qquad (4)$$

where:

- E_0 is the total energy deposited by the particle in the crystal, the goal of the calibration.
- $E(z)$ is the parametrized longitudinal profile of the electromagnetic shower.
- $\mathcal{C}$ represents the transmission of the crystal in the normal conditions, that is when the light is emitted by scintillation along the trajectories of the particles with the spectrum $P(t,T,z,\lambda)$.

$\mathcal{C}$ differs from $\mathcal{B}$ because the light path is clearly not the same as in the light injection. $P(t,T,z,\lambda)$ is independent of time, only $\Lambda(t,z,\lambda)$ is affected by such variation. This is not an assumption but a measurement.
The heart of the calibration performed by the light monitoring system is the parametrization of the global correspondence between $\mathcal{C}$ and $\mathcal{B}$. This correspondence allows the injected light to be related to the electromagnetic shower response of each crystal. A Monte Carlo program [3], based on a model of light propagation in a crystal is used to help make this bridge.

3.4. Calibration

The goal of the calibration with the light monitoring system is to compute E_0 from the value of S.
In the monitoring analysis we work always with ratios because we are interested in variations of quantities (such as transmission terms) rather than in their absolute values. These ratios are close to unity and vary slowly, thus some simplifications can be done: if λ_1 is the wavelength of the light injection system, the ratio of Equations 1 and 4 gives:

$$\frac{S}{E_0} \;=\; \frac{R}{aL} \int \; E(z) \; \frac{\mathcal{C}(t,z,\lambda)}{\mathcal{B}(t,z,\lambda_1)} \; P(t,T,z,\lambda)\; \frac{\bar{M}(V,t,T,\lambda)}{\bar{M}(V,t,T,\lambda_1)} \; d\lambda \; dz \qquad (5)$$

All variables and ratios under the integral sum can be computed by Monte Carlo program or simply monitored.

- the ratio $\frac{\mathcal{C}(t,z,\lambda)}{\mathcal{B}(t,z,\lambda_1)}$ can be tabulated using Monte Carlo program based on measurements performed in the laboratory.
- the ratio: $\frac{\bar{M}(V,t,T,\lambda)}{\bar{M}(V,t,T,\lambda_1)}$ is expected to be pratically independant of the temperature and the voltage variations and should depend slowly of ageing. A good monitoring of the APD should allow a better control of the evolution of this term.

Two monitoring wavelengths in the emission peak of the scintillation would help. A development along λ of the ratios around each monitoring wavelength will simplify the computation of the integral.
The S, R and L values are measured, then E_0 can be computed. Nevertheless, the computation of E_0 still needs a good knowledge of the relative transmission factors a of the fibers.

4. CALIBRATION ON REAL EVENTS

4.1. The method

Two situations must be considered: the calibration of all crystals performed in a high energy electron beam and the *in situ* calibration performed with isolated electrons from the electronic decay of W, Z. In both cases the same calibration method will be used.
It consists in comparing for each event the electron's energy of the test beam (or the electron's momentum in the tracker) with the energy deposited in the calorimeter and spread over several crystals, forming a cluster.
If C_i is the true calibration coefficient of the crystal i and B the energy of the incoming electron, one can write for each event j the relation:

$$\sum_{crystals\ i\ in\ cluster} C_i \cdot E_i = B_j \qquad (6)$$

where E_i is the approximate energy deposited in the crystal i. The energy is *approximate* because we include in this term, the calibration constant of the crystal i obtained with the light monitoring system which is known within the percent. After N events, N equations (6) are obtained and defined an overdetermined system of equations (we have more events than we have crystals):

$$A(j,m) \cdot C_m = B_j \qquad (7)$$

where $j \in [1, N]$ is the event number and m the crystal number with $m \in [1, n]$, n being the number of crystals forming the cluster.
This system can be solved once the decomposition [5] of the matrix A is performed by elementary orthogonal transformation as described by S.A.Householder [6].
The method of calibration described above is well adapted for CMS because it is optimized when the element of detection of the calorimeter contains a large fraction of the incident energy. This is fulfilled by the lead tungstate crystals. Another interesting feature of this method is the stability of the computed coefficients even for crystals which have small statistics.

4.2. time needed for a calibration

As written in the CMS proposal [1], about one week at high luminosity is needed to build a new set of calibration constants for the barrel using electrons from W and Z decays. At lower luminosity (at the beginning of the LHC operation) it is the possible to wait the same amount of time by grouping the crystals and computing a mean absolute calibration coefficient for each set.
In this case the absolute coefficients of each crystal in the set can be nevertheless computed because all the intercalibration constants are known thanks to the light monitoring system.

5. CONCLUSIONS

We have explained how we intend to calibrate the Electromagnetic Calorimeter of CMS with the light monitoring system. The stability of $1-2\%$ on the determination of the absolute electromagnetic energy requiere a very good control of the light monitoring at each step of the distribution system but also some dedicated measurements in the laboratory and the test beam.
We have sketched a method using the Householder approach to calibrate the detector with real events.
Once the calibration has been performed with the light monitoring system, typically one week is needed to calibrate all the channels of the Calorimeter with physical events.

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